NASA/TM-1999-209511

An Experimental Study of a Stitched Composite with a Notch Subjected to Combined Bending and Tension Loading

Susan O. Palmer, Alan T. Nettles, and C. C. Poe, Jr.
Langley Research Center, Hampton, Virginia

August 1999

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/TM-1999-209511

An Experimental Study of a Stitched Composite with a Notch Subjected to Combined Bending and Tension Loading

Susan O. Palmer, Alan T. Nettles, and C. C. Poe, Jr.
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

August 1999

Available from the following:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 487-4650

Introduction

As part of NASA's Advanced Subsonic Technology (AST) Composite Wing Program, a full scale all-composite wing box for a commercial transport aircraft is to be built. The design will address the requirements of the Federal Aviation Regulation (FAR) Airworthiness Standards. This includes the requirement that the wing maintain adequate strength after sustaining discrete source damage from events such as uncontained engine failure (reference 1). In an effort to obtain further insight into the strength and failure modes of composite specimens with through-thickness damage, the experimental study presented in this paper was undertaken. This study is intended to aid in the understanding of how the damaged wing will behave in combined bending and tension loading and to help guide the development of an analytical model of the damaged structure.

Most studies that examine the residual strength of damaged material have used only one mode of loading (i.e. tension, compression or bending); however, in practical applications, a damaged composite will probably experience combined stresses. Combined bending and tension loading of edge-delamination composite specimens has been examined (reference 2) as has fatigue crack growth in aluminum sheet (reference 3). Results for combined tension and bending tests of tapered glass/epoxy rotor hubs for helicopters have been reported (reference 4).

This report describes the results of a series of tests conducted to support development of an analytical model for predicting the failure strains of stitched warp-knit carbon/epoxy composite materials with through-thickness damage in the form of a crack-like notch. Test specimens were subjected to loading in pure bending, pure tension, and combined bending and tension.

A description of the composite material tested is provided in the next section. A definition of the test specimens and apparatuses, the experimental procedures, and a review of the experimental results follow this description. The final section of the report provides summary observations.

Materials

The composite specimens tested in this study were fabricated from a warp-knit fabric made of Tenax™ carbon fiber using technologies adapted from the textile industry (reference 5). The fabric, which was designed for the skin of an all-composite subsonic transport wing, contained fibers in the 0°, ±45°, and 90° directions. By areal weight, 44% of the fibers were configured in the 0° direction, 44% in the ±45° directions, and 12% in the 90° direction. Layers of fabric were stacked and stitched together using a modified lock stitch to form a 3-dimensional preform of the required thickness. Kevlar 29 yarns of 1600 and 400 denier were used for the needle and bobbin threads, respectively. The thickness of the stitched warp-knit fabric is 0.056 inches per layer. The specimens used in this study contained eight layers of this fabric, with a total thickness of 0.445 inches. The panels were stitched in the 0° fiber direction at a stitch density of 8 stitches/inch, and the rows of stitches were 0.2 inches apart.

After stitching, the preforms were infiltrated with 3501-6 epoxy using a resin-film-infusion process. The specimens were machined from a 35 by 44 inch plate fabricated at NASA Langley Research Center.

Test Specimens and Apparatuses

Three test methods were used to measure the material's notched failure strain: tension, combined bending and tension, and four-point bending. Each specimen was 0.445 inches thick and 4.00 inches wide, with a 3.00 inch center crack-like notch. The notches were made using an ultrasonic cutting machine and carborundum slurry. All notches had a width of 0.020 inches. Four strain gages were mounted back to back on all specimens. The gages were centered halfway between the notch tip and specimen edge. The gage had a 0.125 inch wide footprint, with a 0.063 inch wide active sensing area. The geometry of all the test specimens (4.00 inches wide, 4.00 inches long between the grips with a 3.00 inch notch length) was designed for the combined bending and tension test. The geometry was selected to force the specimen to fail at small loads while there was still significant bending, which will be discussed later. The crack opening displacement (COD) gage was located at the center of the notch and measured the displacement on the specimen surface.

The exact location of the strain gage is critical because the strain gradient is very large in the area between the notch tip and the specimen edge. Small variations in gage location can result in large differences in readings. Also material non-uniformity and twisting or uneven loading in the test fixture can create measurable deviations in the recorded data.

Center Notch Tension Test

The tension test specimens were 11.5 inches long and mounted directly in the grips of the testing machine. The longitudinal test area between the grips was 4.0 inches. Two specimens were tested in this load condition. The results were consistent for both specimens, therefore the results from one of the specimens will be shown later in this report. The specimen geometry is shown in figure 1. Loads were directly applied to the specimen through the grips of the testing machine.

Center Notch Combined Bending and Tension Test

The combined bending and tension test specimens were 14.0 inches in length. The specimen geometry and the test fixture diagram are shown in figures 2 and 3, respectively. Loads were transmitted to the specimen through the pin/clevis connections at the top and bottom grips. The axial load provided the mean tensile strains in the specimen, and using offset shims of various thicknesses placed between the plane of the specimen and the loading line provided the bending strains. The offset values used were approximately 0.22, 0.42, 0.61, 0.80, and 0.96 inches, with one specimen tested for each offset value. Figure 4 is a photograph of the specimen and test apparatus mounted in the testing machine.

Center Notch Four-point Bend Test

The four-point bend test specimen was 17.5 inches long. The center crack-like notch was 3.00 inches long. The center 2.50 inches of notch length had an enlarged width of 0.045 inches, as shown in figure 5, to prevent the notch from fully closing in compression. Two specimens were tested in this load condition. The results were consistent for both specimens, therefore the results from one of the specimens will be shown later in this report. The specimen in the test fixture is schematically illustrated in figure 6. Loads were applied to the top and bottom rollers resulting in constant bending moments between the two top (interior) rollers.

Experimental Procedures

All tests were conducted with displacement controlled at a fixed ramp rate for each of the different test conditions. Measurements of strain near notch tips, crack opening displacement (COD), and applied load were monitored in all tests. The out-of-plane displacement at the center of the notch was also measured, with a Linear Variable Differential Transformer (LVDT), when the specimen was subjected to bending. The LVDT instrument slipped during testing of the specimen in combined bending and tension with an offset of 0.61 inches; therefore, out of plane displacement measurements are not available for that test. Data was recorded once per second for the combined bending and tension tests. Data was obtained by stopping the loading process at given increments and manually recording the displayed instrument values, for pure bending and pure tension tests.

Experimental Results

The geometry of the specimens (4 inches wide, 4 inches long between the grips with a 3 inch notch length) was selected to force the specimen to fail at small loads while there was still significant bending. This problem is illustrated in figure 7. The non-linearity of the bending strains along the length of the specimen is due to the apparatus design which introduced bending into the specimen by applying an eccentric tension load. Because strength increases with decreasing notch length, the bending strain at failure (the difference in the compressive and tensile strains) would decrease with decreasing notch length. Thus, the long notch length caused the specimen to break at a low load while bending was still significant.

Another problem that was realized was that the apparatus design for the combined bending and tension tests created a non-linear relationship between bending and tension as illustrated in figure 8. As L_g/L (the ratio of the distance between pin and fixture end to the length of the test section) increases, so does the non-linearity. The apparatus for combined bending and tension tests was designed with L_g/L equal to 1.875.

Center Notch Tension Test

The measured strains of one of the center notch tension tests are summarized in figure 9. Note the different strains measured by each of the four gages. This difference highlights the criticality of strain gage placement and the influence of non-homogeneous characteristics of the specimens because the load versus strain curves should have been approximately the same. All gages exhibited non-linear behavior at approximately 4,000 $\mu\varepsilon$. When surface strains reached approximately 6,000 $\mu\varepsilon$, significant damage occurred. Figure 10 shows the crack opening displacement (COD) measured from the test. The COD measurement becomes nonlinear at approximately 30,000 lbs, which agrees with the start of non-linear behavior in the strain data presented in figure 9. This nonlinearity is probably due to the start of crack extension (damage onset).

Center Notch Combined Bending and Tension Test

Five combined bending and tension tests were conducted, one each for the five offset values described previously. The results of the center notch combined bending and tension tests are summarized in figures 11 through 13 for the 0.22 inch offset. These plots illustrate the strains and displacements of the experimental data. For completeness, all results for the other offset values are included in figures 14-16.

During testing of the combined bending and tension and the pure bending specimens, the specimens were loaded so that strain gages on one side were being compressed while the gages on the other side were in tension; strain gages 1 and 3 were on the compressed side of the specimens while strain gages 2 and 4 were on the tension side of the specimens. In figure 11 it can be seen that the failure strain at the surface was greater than the 6,000 $\mu\varepsilon$ found in the pure tension tests. The strain from gage 4 is increasing faster than the strain from gage 2. The difference is probably due to the notch advancing unevenly. Therefore, gages 1 and 3 are providing a more accurate picture of the trend that generally occurs with increased load. Thus, as shown by gages 1 and 3, when bending was involved, the failure strain measured by the strain gages increased. In figure 12, it is interesting to observe that the out of plane displacement increases till the offset (eccentricity) is significantly reduced. Thus, bending moment decreases with increasing load. This non-linear relationship between bending and tension is due to the apparatus design. In figure 13, the crack opening displacement data responses distorted at the same load as the compressive side strain gages, as indicated in figure 11.

As also seen in the specimens with the larger eccentricities (figure 14), as more bending moment was introduced into the specimen, the measured strain at failure increased. The 0.96 inch offset specimen failed in compression before the tensile side had a chance to reach the larger strains. The 0.80 inch offset specimen was observed to have some compressive failure, but this does not entirely explain why the failure strain of this specimen was lower than those with less bending. The 0.22, 0.42, and 0.61 inch offset specimens appeared to have tensile failure.

Center Notch Four-point Bend Test

Test data from one of the center notch four-point bend tests are shown in figures 17 and 18. The specimen withstood surface strains at the strain gage location of approximately 10,000 $\mu\varepsilon$ in tension and approximately 11,000 $\mu\varepsilon$ in compression prior to failure. The specimen failed on the compressive side because the material has a lower compressive strength. A series of tests were performed on test coupons, the tensile strength along the 0° fibers is 131,000 PSI and the compressive strength is 87,000 PSI. The combined bending and tension specimens with the two largest offset values also failed on the compressive side. A comparison of the tension only and bending only tests show that these specimens experienced a much larger strain in flexure than in pure tension. In figure 18, the crack opening displacement data responses distorted at the same moment load as the compressive side strain gages indicated in figure 17, approximately 2,300 in-lbs.

Discussion

Material non-uniformity including stitching location relative to gage location, twisting or uneven loading in the test fixture, and slight deviations of the location of the gages created measurable deviations in the recorded data. Also, the strain gages average the strain field under the gages. Thus, the measured strains were assumed to exist at the centroid of the gage. This assumption is exact only for linearly varying strains.

The strains due to bending were larger at failure than those for pure tension. Similar results for unnotched composite specimens have been reported in several studies (references 6,7,8 and 9), which show that a larger failure stress (strain) is measured in flexural (bending) specimens because much less material is under the maximum tension stress. In a tension test, the entire volume under the gage is at the same applied tensile stress. A Weibull statistical analysis, which accounts for probability of defects in a given volume of material, agrees well with the measured data for flexural specimens. This concept has also been used to explain the differences in tensile strength between small and large test specimens in which the smaller specimens are always stronger (reference 10).

The results of the center notch four-point bend test indicated that the maximum tensile strain at the strain gage location was approximately 10,000 $\mu\varepsilon$ and the compressive strain was approximately 11,000 $\mu\varepsilon$ before failure. The specimen failed on the compressive side because the material has a lower compressive strength. The combined bending and tension specimens with the two largest offset values also failed on the compressive side. By comparing the tension only and bending only tests, it was shown that these specimens could experience a much larger strain in flexure than in pure tension.

The non-linear relationship due to the combined bending and tension apparatus was significant. However, this did not preclude the validity of the observations that were made. The results of the combined bending and tension test indicated that the maximum tensile strain at the strain gage location, for those specimens that failed in tension (small offset, 0.22 inches), was approximately 10,000 $\mu\varepsilon$ before failure. For those specimens that failed in compression (large offset, 0.96 inches) was approximately 9,000 $\mu\varepsilon$. When no bending stresses were present in the pure tension test, however, the maximum tensile strain at the strain gage location only reached about 6,000 $\mu\varepsilon$ before failure. These results indicate that the presence of bending stresses in the specimens significantly increased the maximum strain experienced before failure.

Figure 19 shows the true bending moment to tension (axial) relationship for the different load configurations just before failure. The true bending moment was determined using the LVDT values and shim offset values to compute the actual moment arm at the failure load. The 0.22, 0.42, and 0.61 inch offset specimens appeared to have tensile failure while the 0.80 and 0.96 inch offset specimens appear to have compressive failure.

Summary

A series of exploratory tests were conducted to determine the failure strain of stitched multi-axial warp-knit composite material containing through-thickness damage. Specimens subjected to pure tension, combined bending and tension, and pure bending were evaluated. The bending strain contribution in the combined bending and tension tests was significant and should not be ignored.

These data provide information on the effectiveness of the test methods and on general trends in the material response. The limited amount of test material and time available limited the scope of the investigation.

The values of failure strain indicate that the more a specimen bends, the larger the amount of strain the outer surface can experience before failure. A larger failure stress (strain) has been shown to exist in composite specimens while under flexure compared to pure tension testing. A Weibull statistical analysis, which takes into account the volume of material experiencing the maximum stress, has done well in predicting the maximum stress (strain) experienced by a specimen due to these two types of loading. Apparently, the presence of a notch, which greatly reduces the volume of material that experiences the maximum stress in a tension test, does not diminish the effect of flexure strength being greater than tensile strength. Thus one cannot assume a composite will fail whenever a volume of material, regardless of size, experiences a maximum stress or strain value as determined from tensile testing. Fortunately, if this assumption is made, the error will be on the conservative side.

Any attempt at developing an analytical model for failure when subjected to combined bending and tension loads must take into account the volume of material experiencing the maximum stress, even when a stress riser such as a notch is present. Care must also be taken to account for compressive stresses which can cause failure of the specimen, as they did for the 0.96 inch offset value.

References

1. Poe, Jr. C. C., “Residual Strength of Composite Aircraft Structures with Damage,” *ASM Handbook, Vol. 19, Fatigue and Fracture*, 1996, pp. 920-935.
2. Armanios, E.A. and Rehfield, L.W., "Interlaminar Fracture Analysis of Composite Laminates Under Bending and Combined Bending and Extension," *Composite Materials: Testing and Design (Eighth Conference), ASTM STP 972*, J.D. Whitcomb, Eds., American Society for Testing and Materials, Philadelphia, 1988, pp. 81-94.
3. Phillips, E.P., "An Experimental Study of Fatigue Crack Growth in Aluminum Sheet Subjected to Combined Bending and Membrane Stresses," NASA TM 4784, October, 1997.
4. O'Brien, T.K. and Murri, G.B., "Combined Tension and Bending Testing of Tapered Composite Laminates," *Applied Composite Materials*, Vol. 1, 1995, pp. 401-413.
5. Masters, John E., "Translaminar Fracture Toughness of a Composite Wing Skin Made of Stitched Warp-knit Fabric," NASA CR-201728, November, 1997.
6. Kaminski, B.E., "Narmco 5208/T300 - A Graphite-Epoxy System Engineered for High-Performance Aircraft Structures," *Proceedings of the Fifth National SAMPE Technical Conference*, New York, October, 1972, pp. 11-17.
7. Bullock, R.E., "Strength Ratios of Composite Materials in Flexure and in Tension," *Journal of Composite Materials*, Vol. 8, April 1974, pp. 200-206.
8. Zweben, C., "The Flexural Strength of Aramid Fiber Composites," *Journal of Composite Materials*, Vol. 12, October 1978, pp. 422-430.
9. Whitney, J.M. and Knight, M., "The relationship Between Tensile Strength and Flexure Strength in Fiber Reinforced Composites," AFWAL-TR-80-4104, December, 1980.
10. Kellas, S. and Morton, J., "Strength Scaling in Fiber Composites," NASA CR 4335, November, 1990.

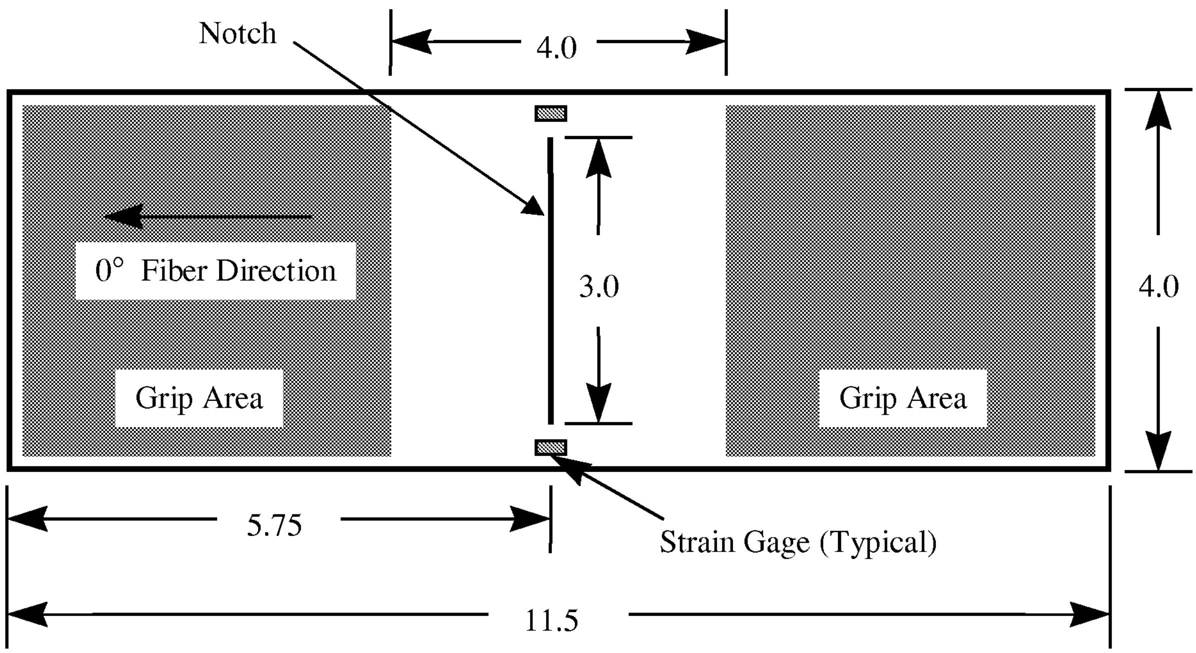


Figure 1. Center notch tension specimen geometry (Dimensions in inches).

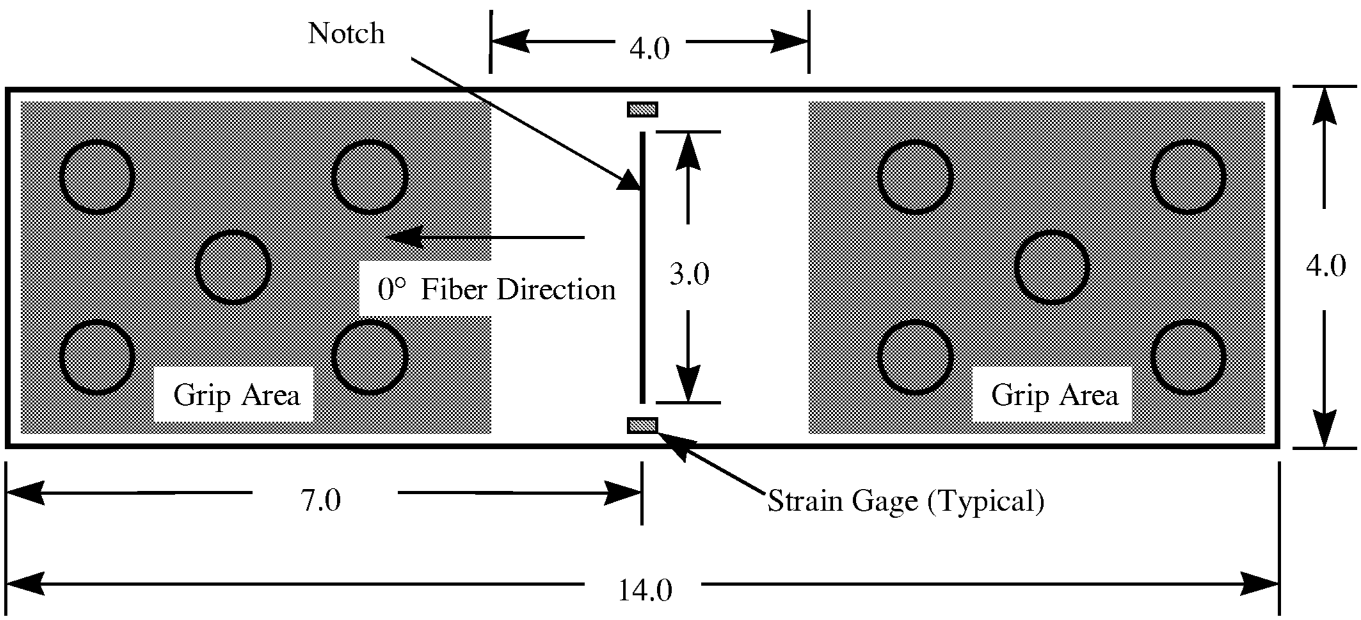


Figure 2. Center notch combined bending and tension specimen geometry (Dimensions in inches).

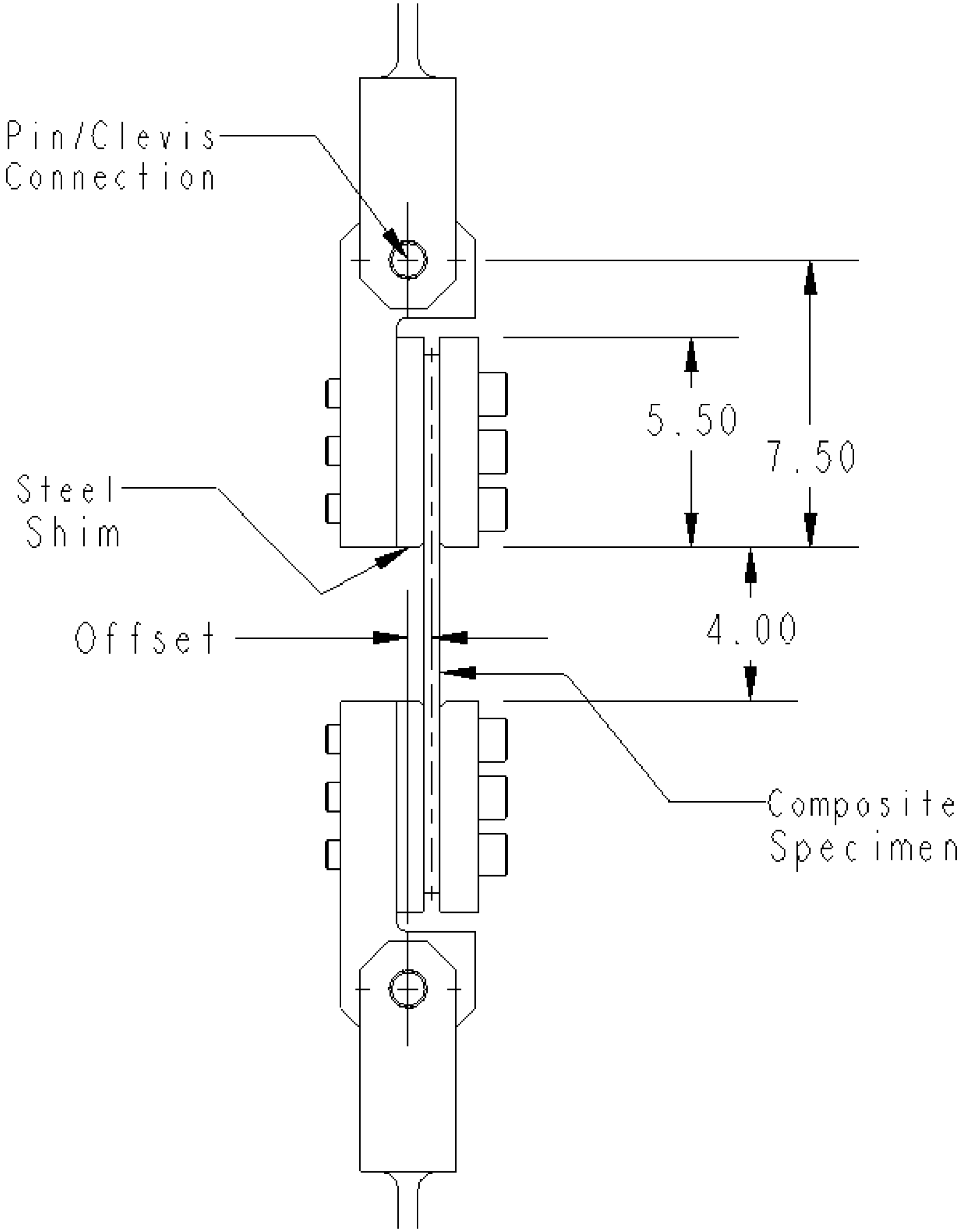


Figure 3. Combined bending and tension fixture diagram (Dimensions in inches).

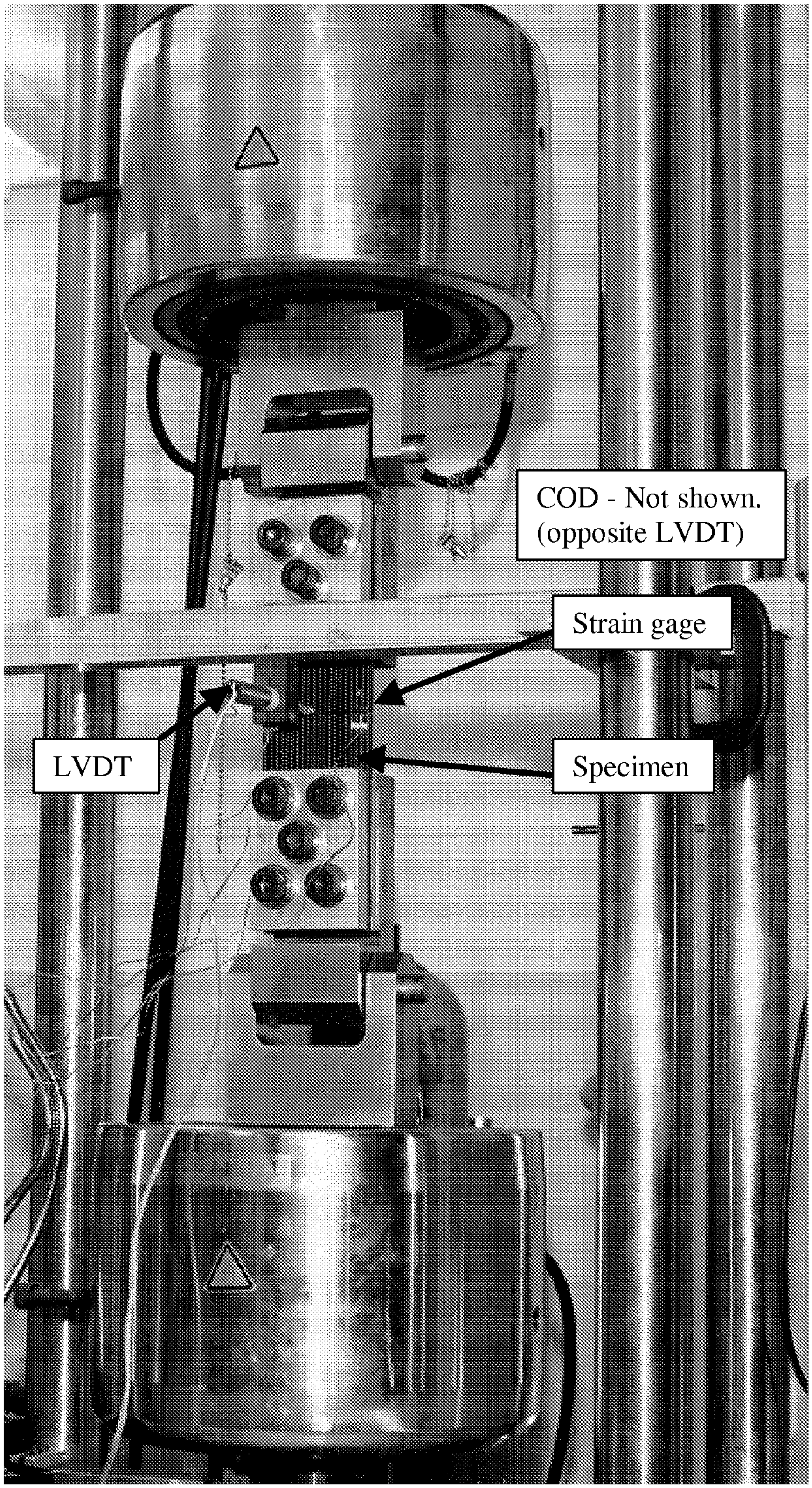


Figure 4. Combined bending and tension fixture photograph.

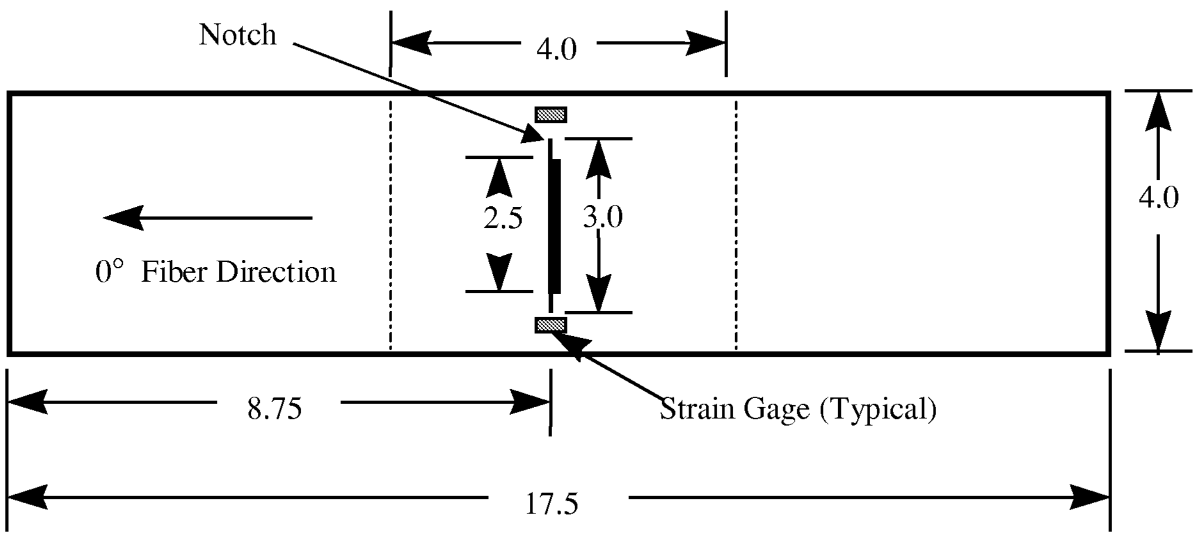


Figure 5. Center notch four-point bend test specimen geometry (Dimensions in inches).

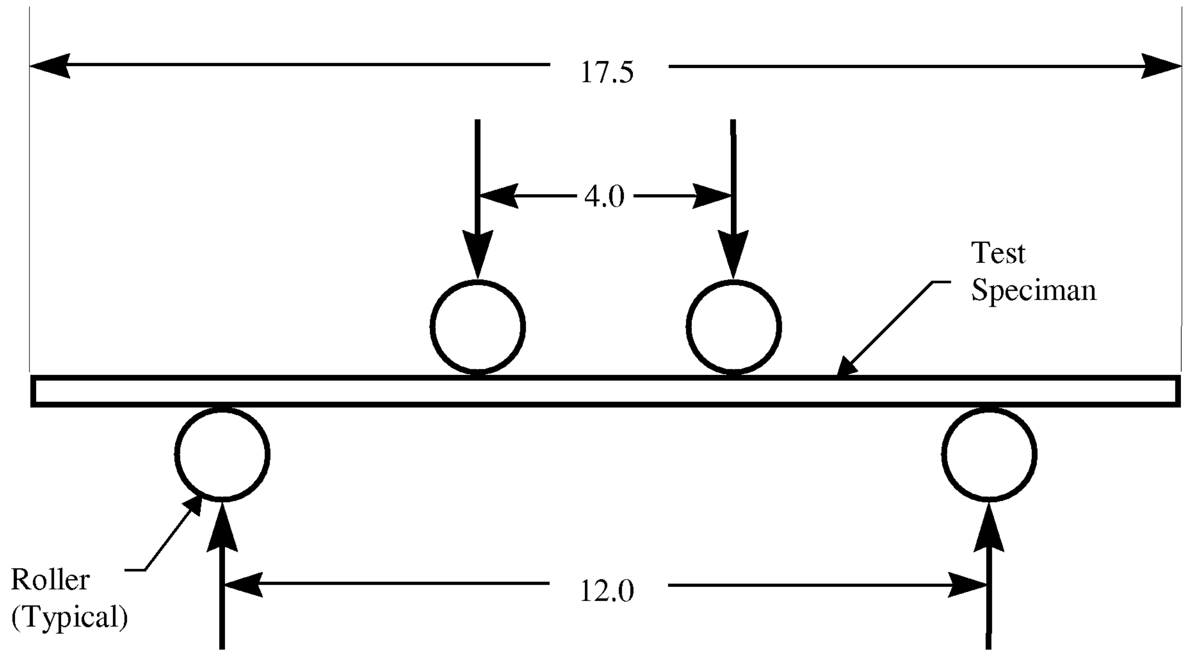


Figure 6. Schematic illustration of center notch four-point bend test (Dimensions in inches).

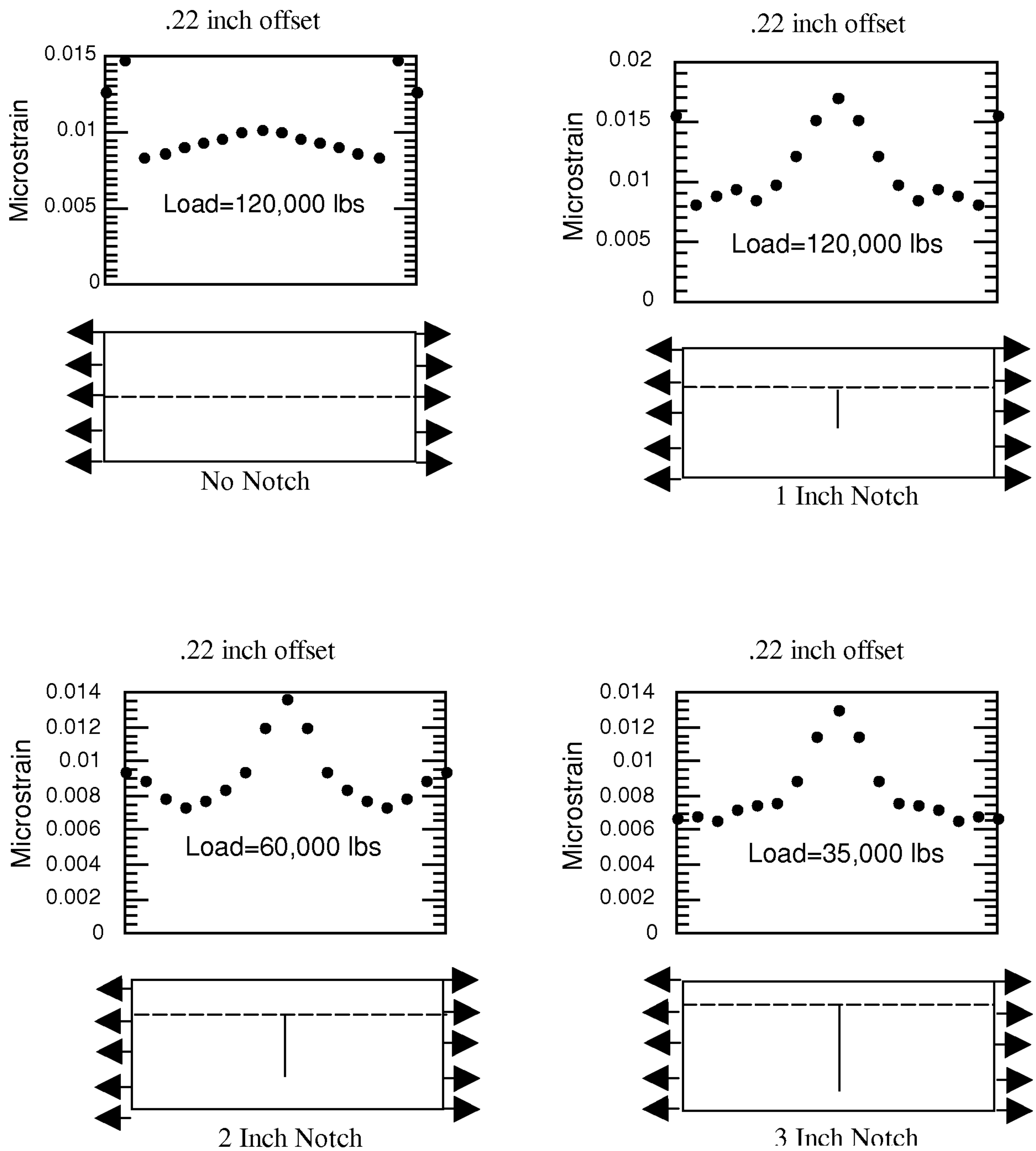


Figure 7. Plots of finite element results for longitudinal strain along specimen length at a .22 inch offset. Specimen is 4 inches wide. Strains were taken along dashed lines illustrated in each figure below each plot.

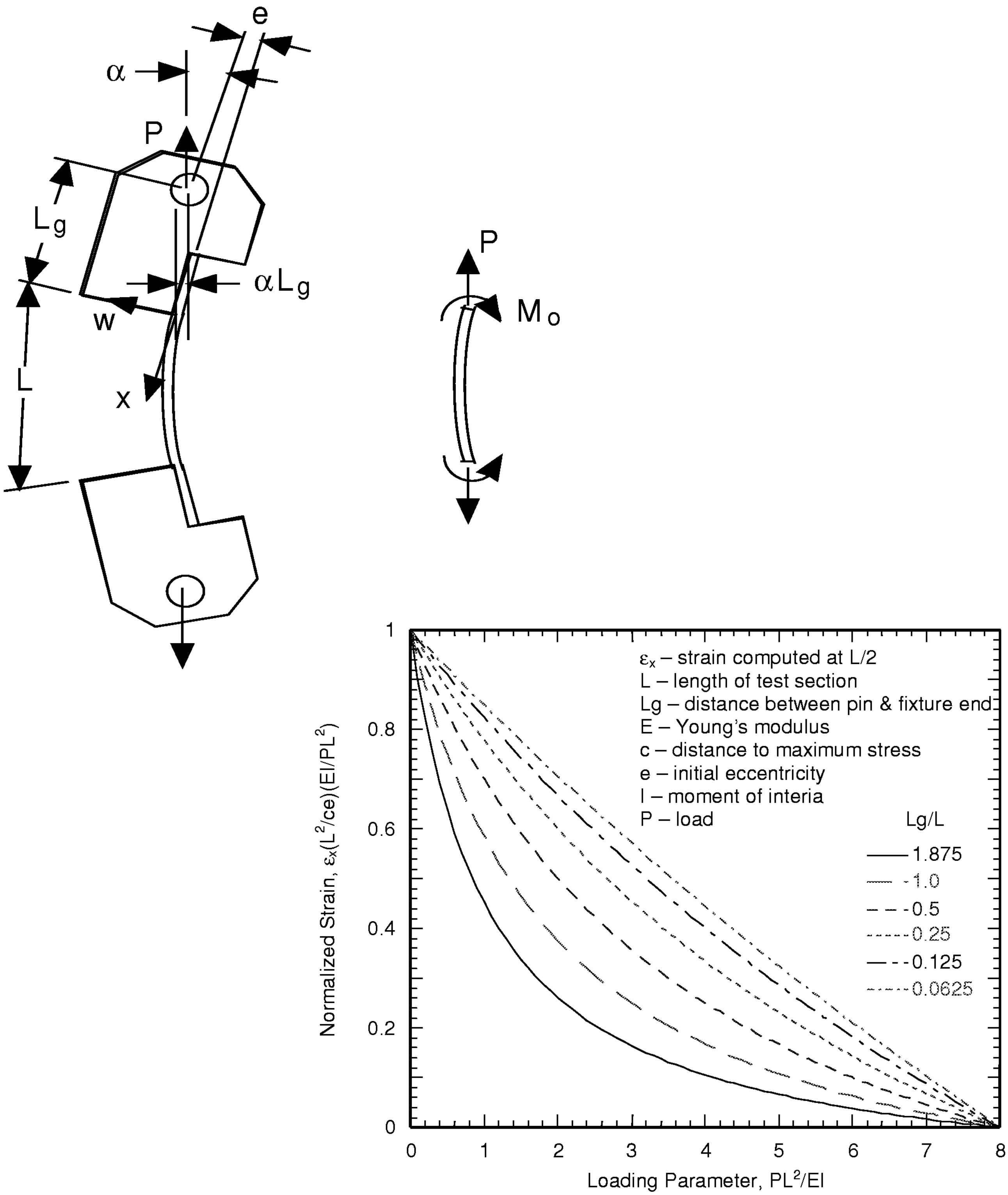


Figure 8. Normalized strain versus loading parameter to illustrate how apparatus design influences non-linearity.

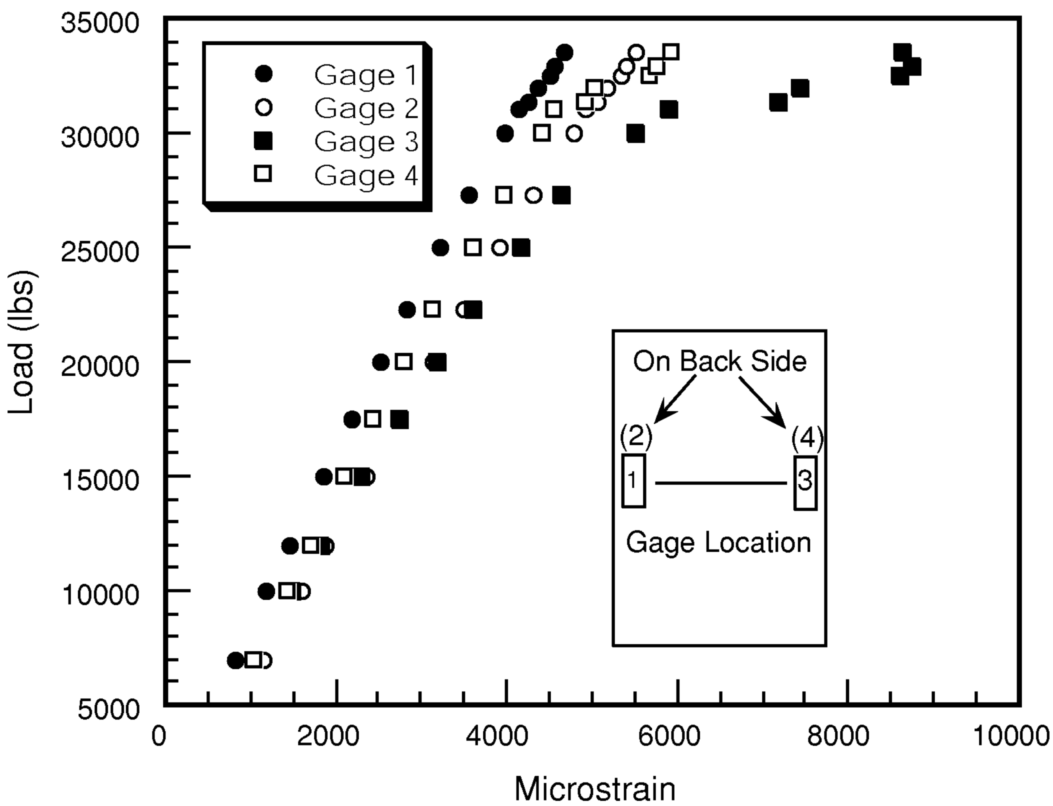


Figure 9. Load versus strain for pure tension test.

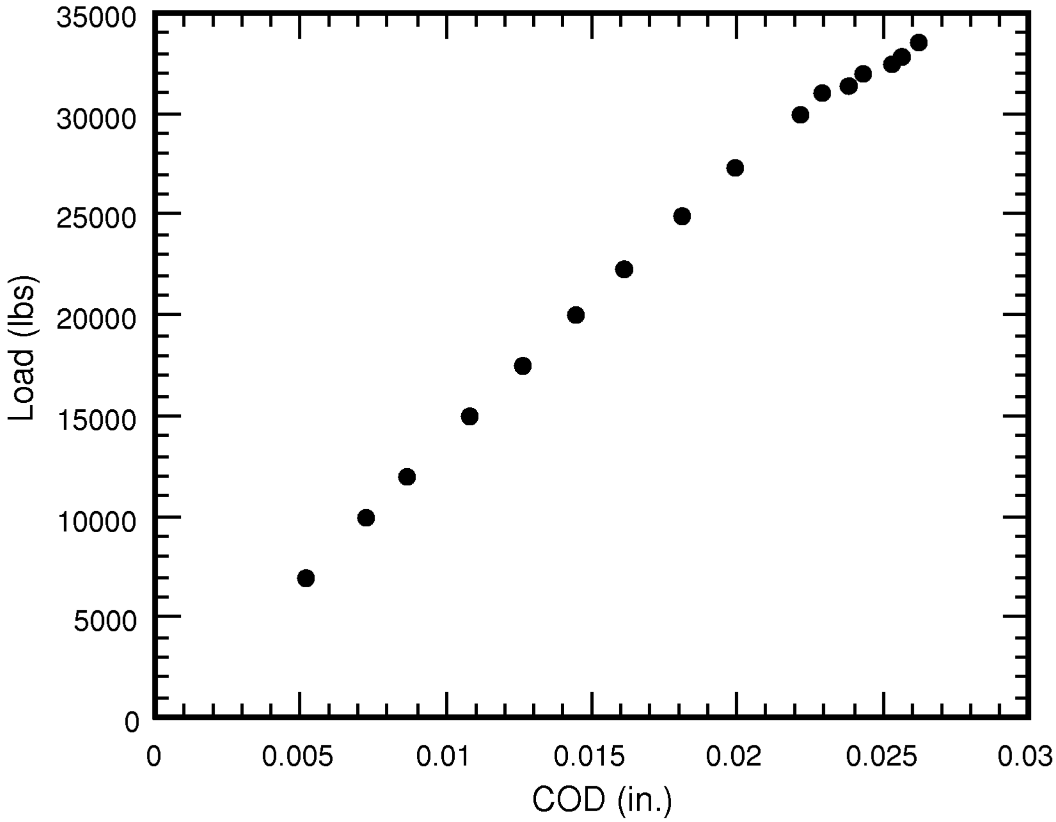


Figure 10. Load versus crack opening displacement for pure tension test.

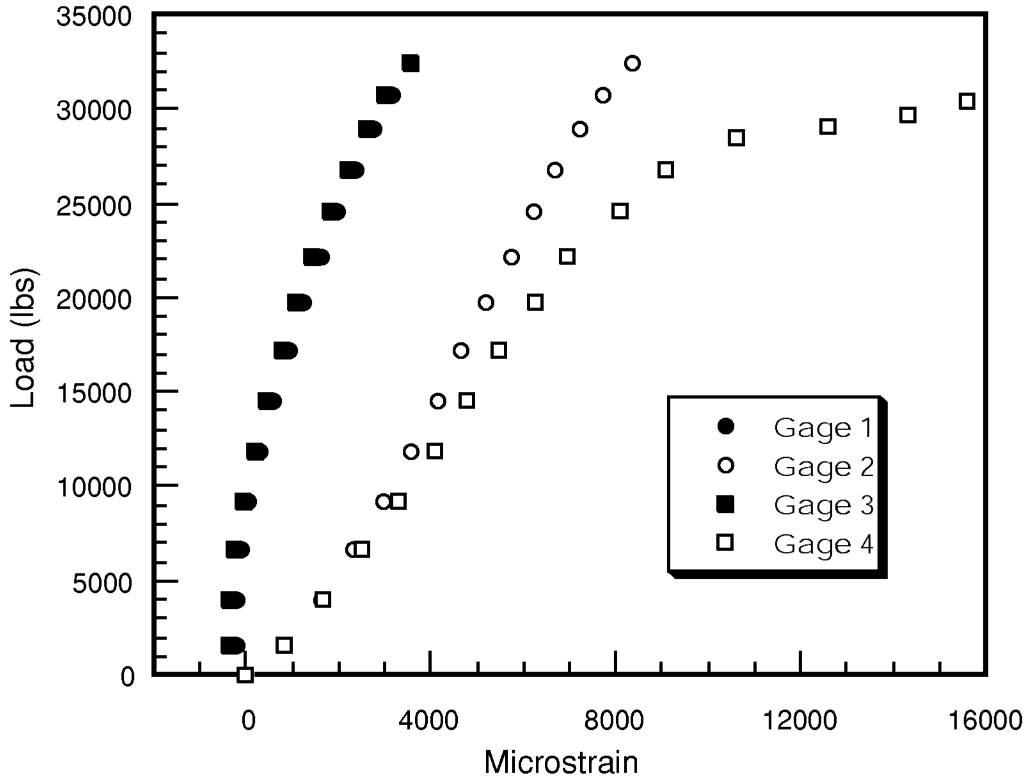


Figure 11. Load versus strain for 0.22 inch offset in combined bending and tension load test.

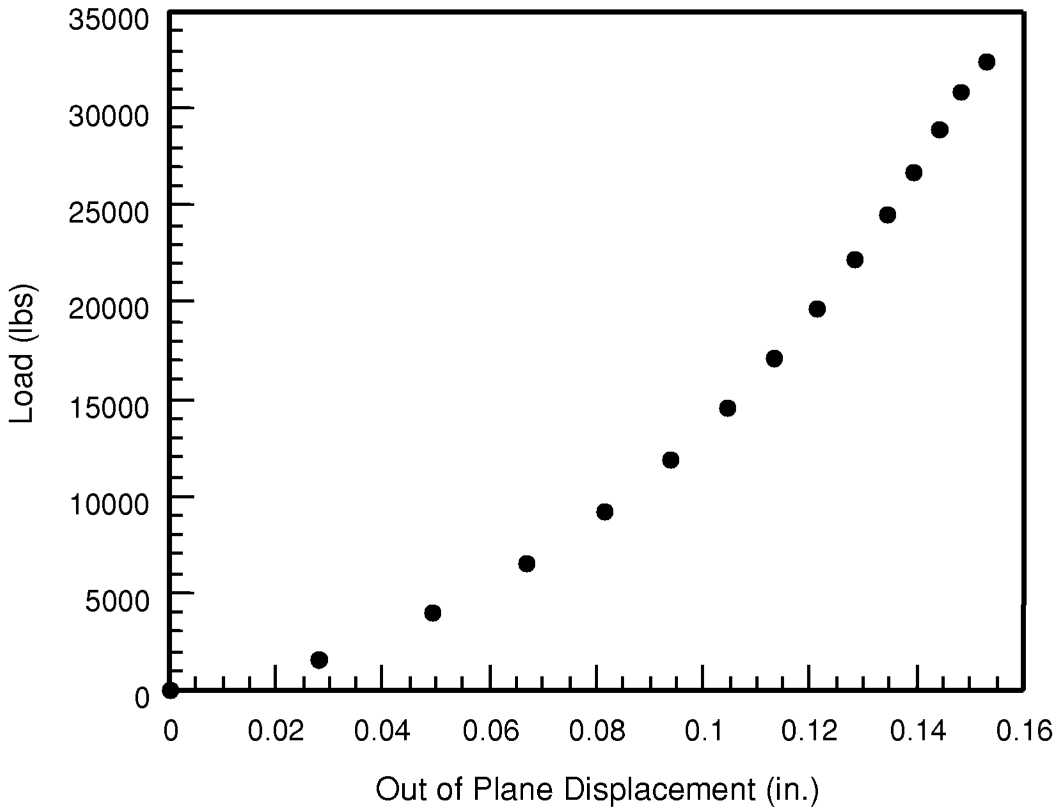


Figure 12. Load versus out of plane displacement for 0.22 inch offset in combined bending and tension load test.

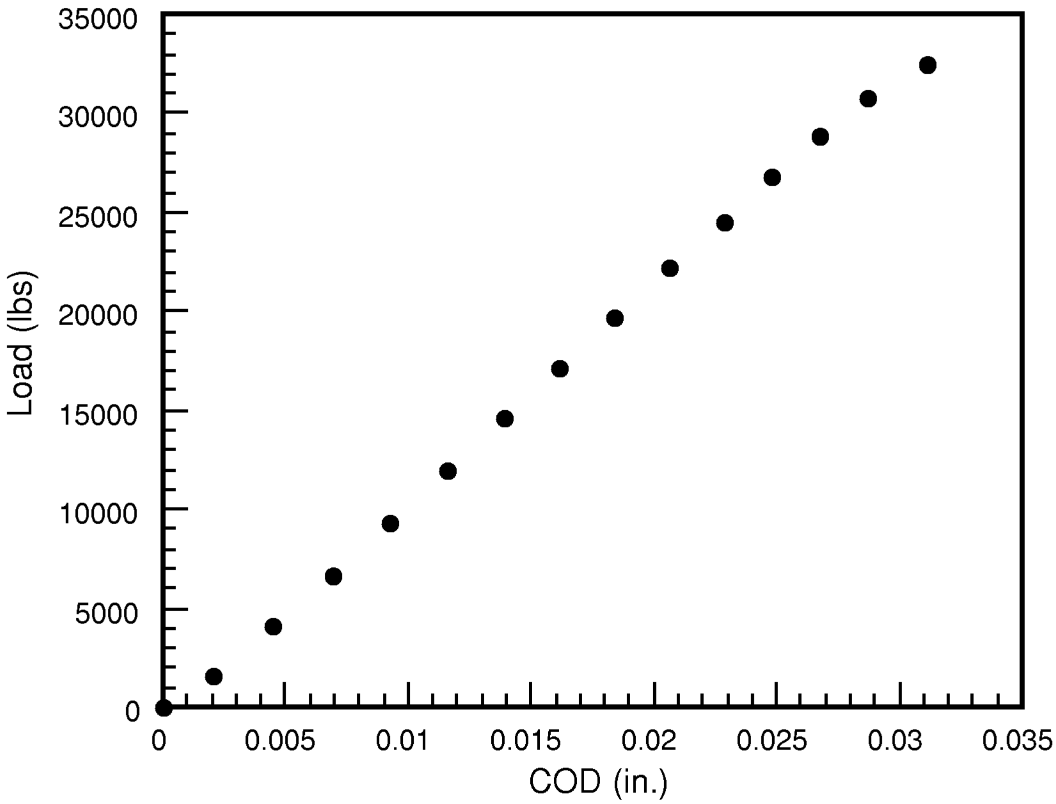
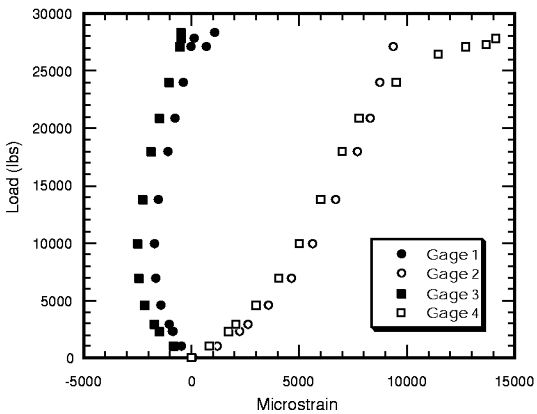
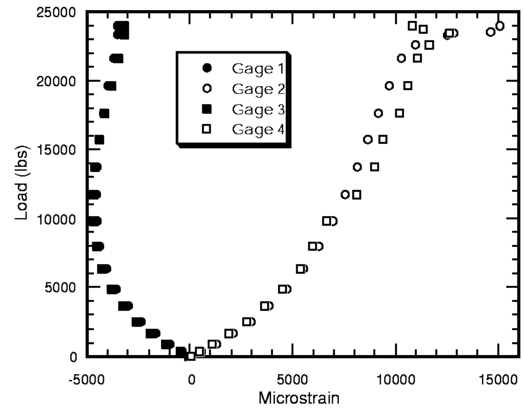


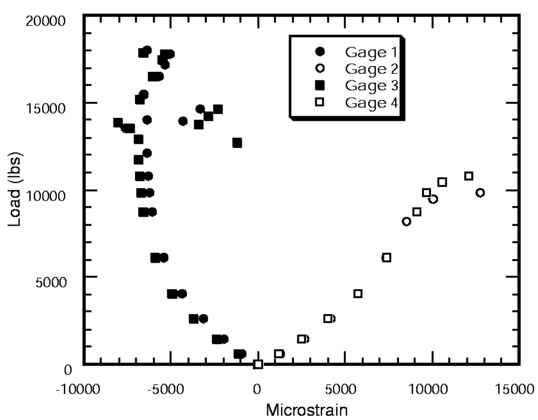
Figure 13. Load versus crack opening displacement for 0.22 inch offset in combined bending and tension load test.



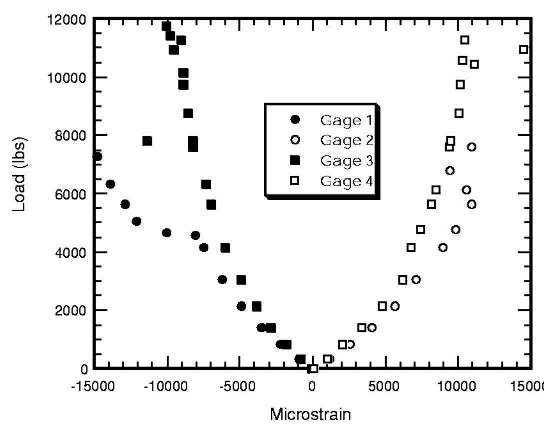
(a)



(b)



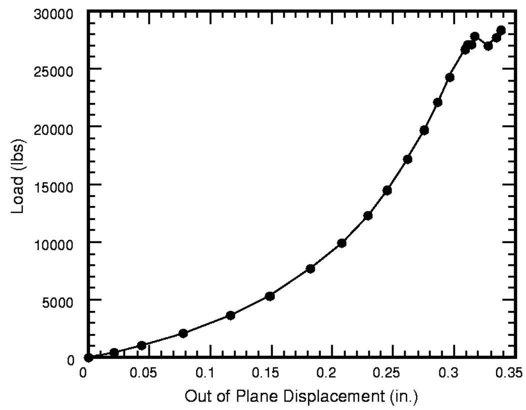
(c)



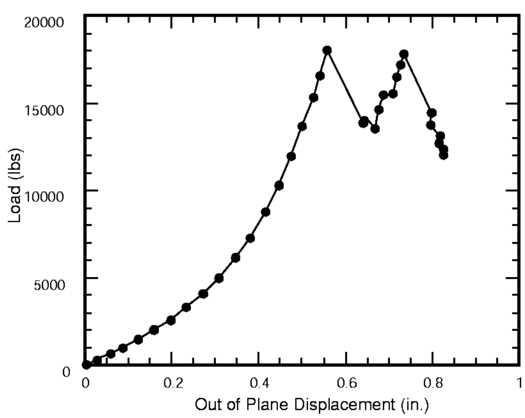
(d)

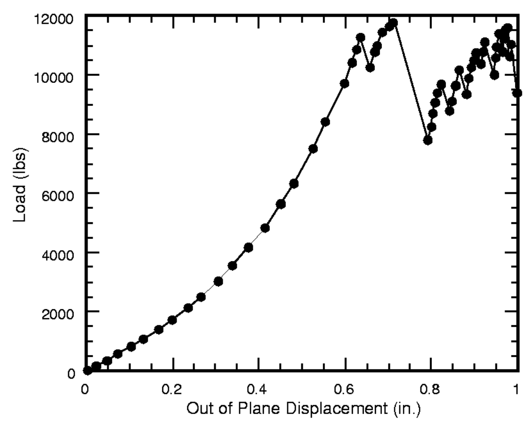
(a) 0.42 inch offset. (b) 0.61 inch offset.
(c) 0.80 inch offset. (d) 0.96 inch offset.

Figure 14. Load versus strain in combined bending and tension load tests.



(a)



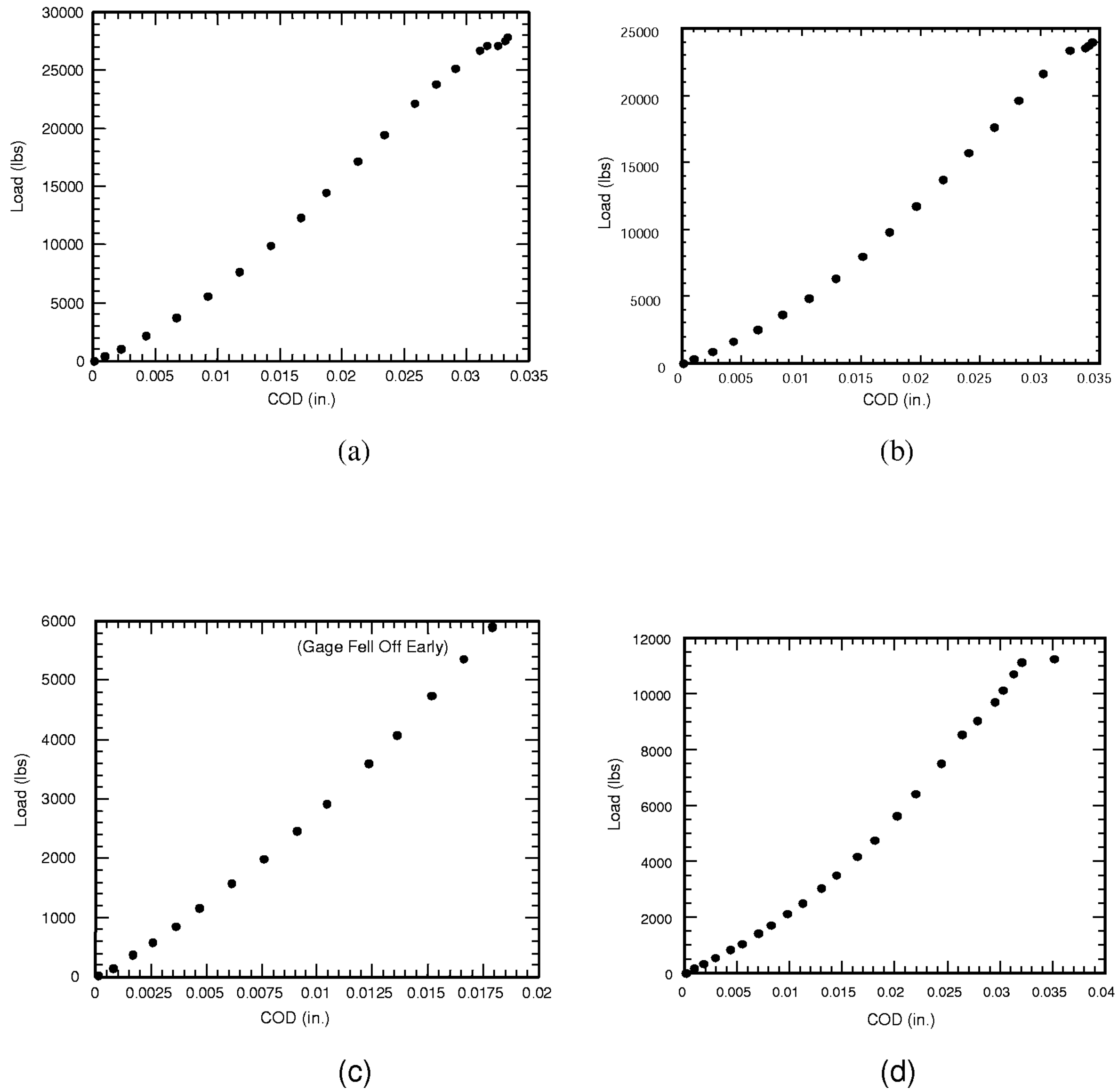


(b) (c)

(a) 0.42 inch offset.

(b) 0.80 inch offset. (c) 0.96 inch offset.

Figure 15. Load versus out of plane displacement in combined bending and tension load tests.



(a) 0.42 inch offset. (b) 0.61 inch offset.
(c) 0.80 inch offset. (d) 0.96 inch offset.

Figure 16. Load versus crack opening displacement in combined bending and tension load tests.

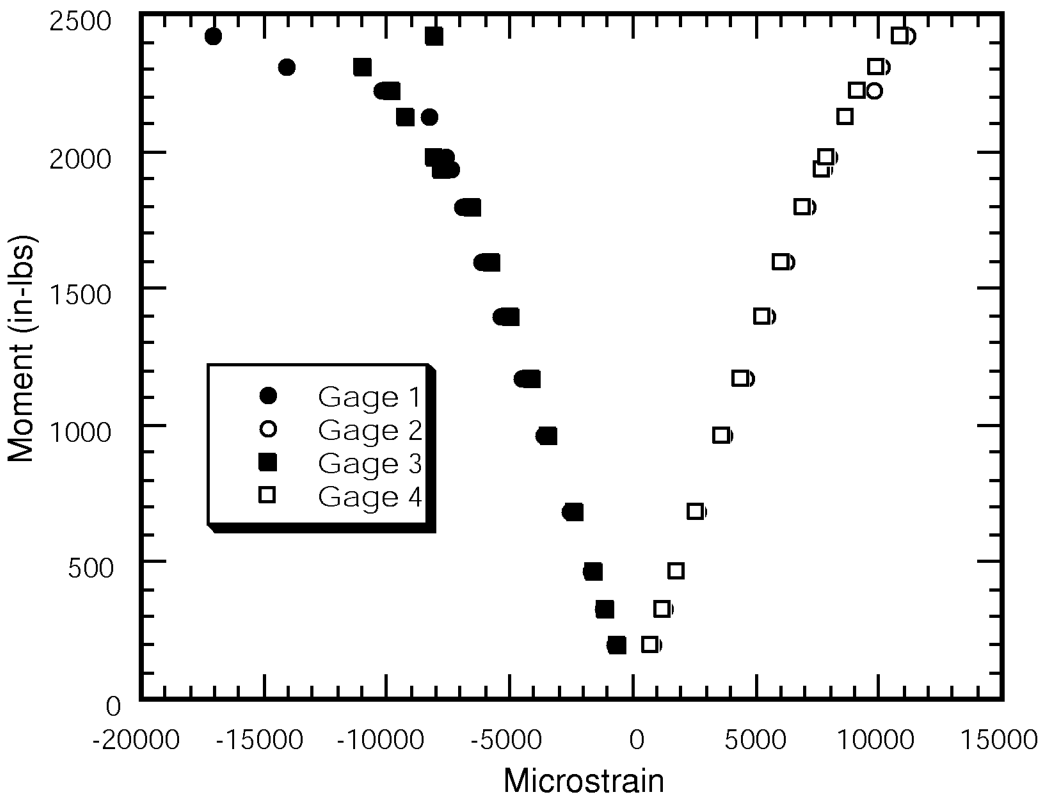


Figure 17. Moment versus strain for four-point bend load test.

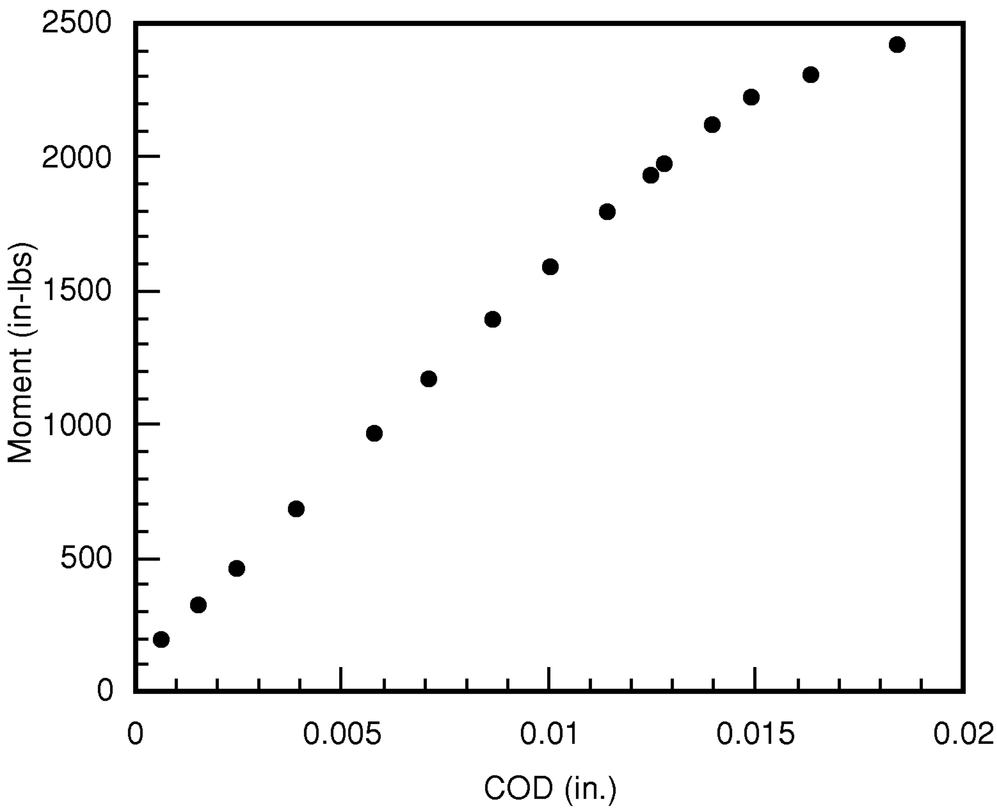


Figure 18. Moment versus crack opening displacement for four-point bend test.

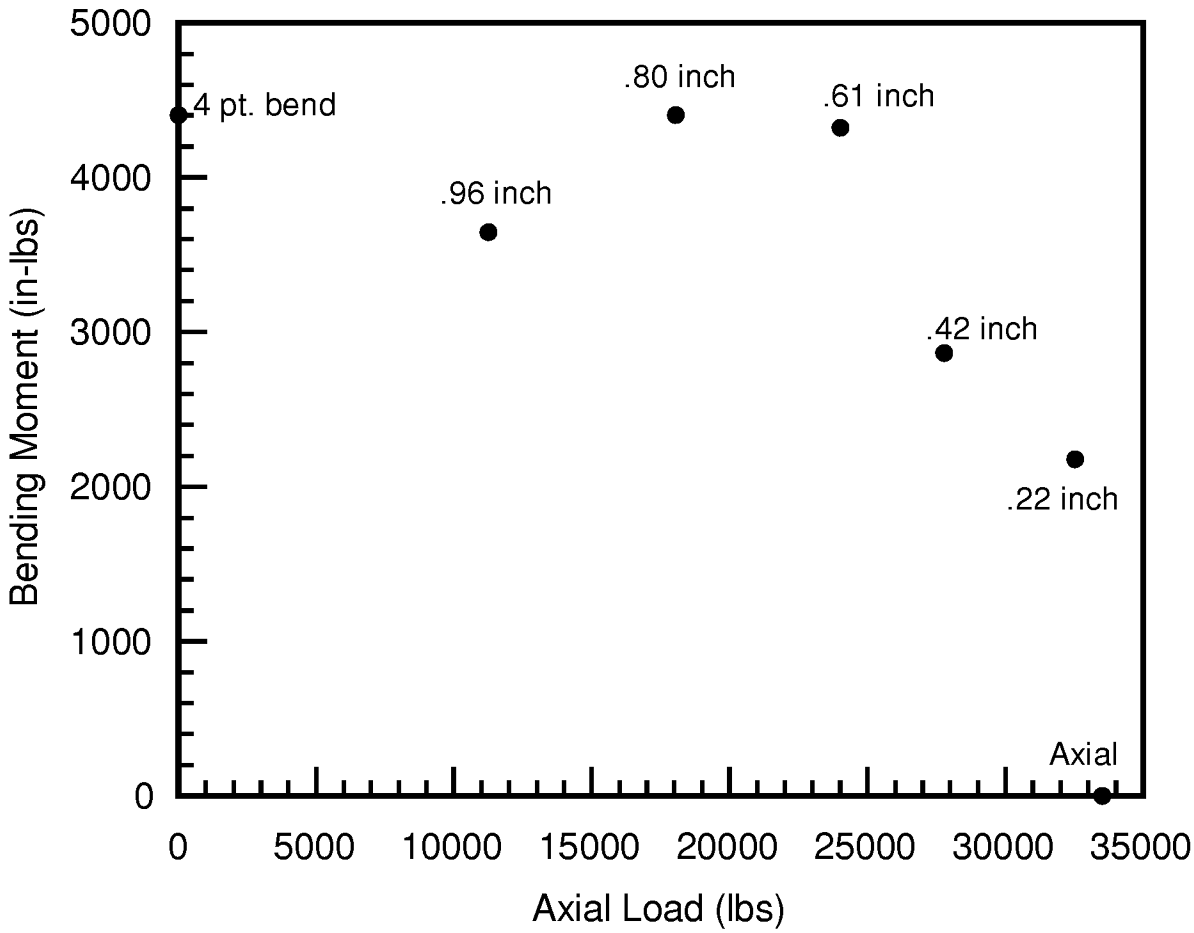


Figure 19. Bending moment versus axial load for all test types just before failure.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
August 1999

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
An Experimental Study of a Stitched Composite with a Notch Subjected to Combined Bending and Tension Loading

5. FUNDING NUMBERS
538-10-11-05

6. AUTHOR(S)
Susan O. Palmer, Alan T. Nettles, and C. C. Poe, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17884

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-1999-209511

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 24 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)
A series of tests was conducted to measure the strength of stitched carbon/epoxy composites containing through-thickness damage in the form of a crack-like notch. The specimens were subjected to three types of loading: pure bending, pure tension, and combined bending and tension loads. Measurements of applied loads, strains near crack tips, and crack opening displacements (COD) were monitored in all tests. The transverse displacement at the center of the specimen was measured using a Linear Variable Differential Transformer (LVDT). The experimental data showed that the outer surface of the pure tension specimen failed at approximately 6,000 microstrain, while in combined bending and tension loads the measured tensile strains reached 10,000 microstrain.

14. SUBJECT TERMS
Stitched laminates; Combined loading; Bending; Tensile strain; Notch strength

15. NUMBER OF PAGES
31

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL